

# APPROACHES TO NUMERICAL MODELING IN THE DEVELOPMENT PROCESS OF COMPLEX STRUCTURES FOR FUSION DEVICES

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SOFE 2013 WO3-2

# Outline

Introduction

Approaches

- Simplified beam/shell approach  
*(Busbar system for W7-X)*
- Multifield analysis including electromagnetic transients  
*(ITER diagnostic port plug)*
- Engineering material model for serration effect  
*(W7-X magnet system)*

Conclusions

# Introduction

Components in fusion experiments subject to **multiple loads** of different nature together with **lack of space** for supports.

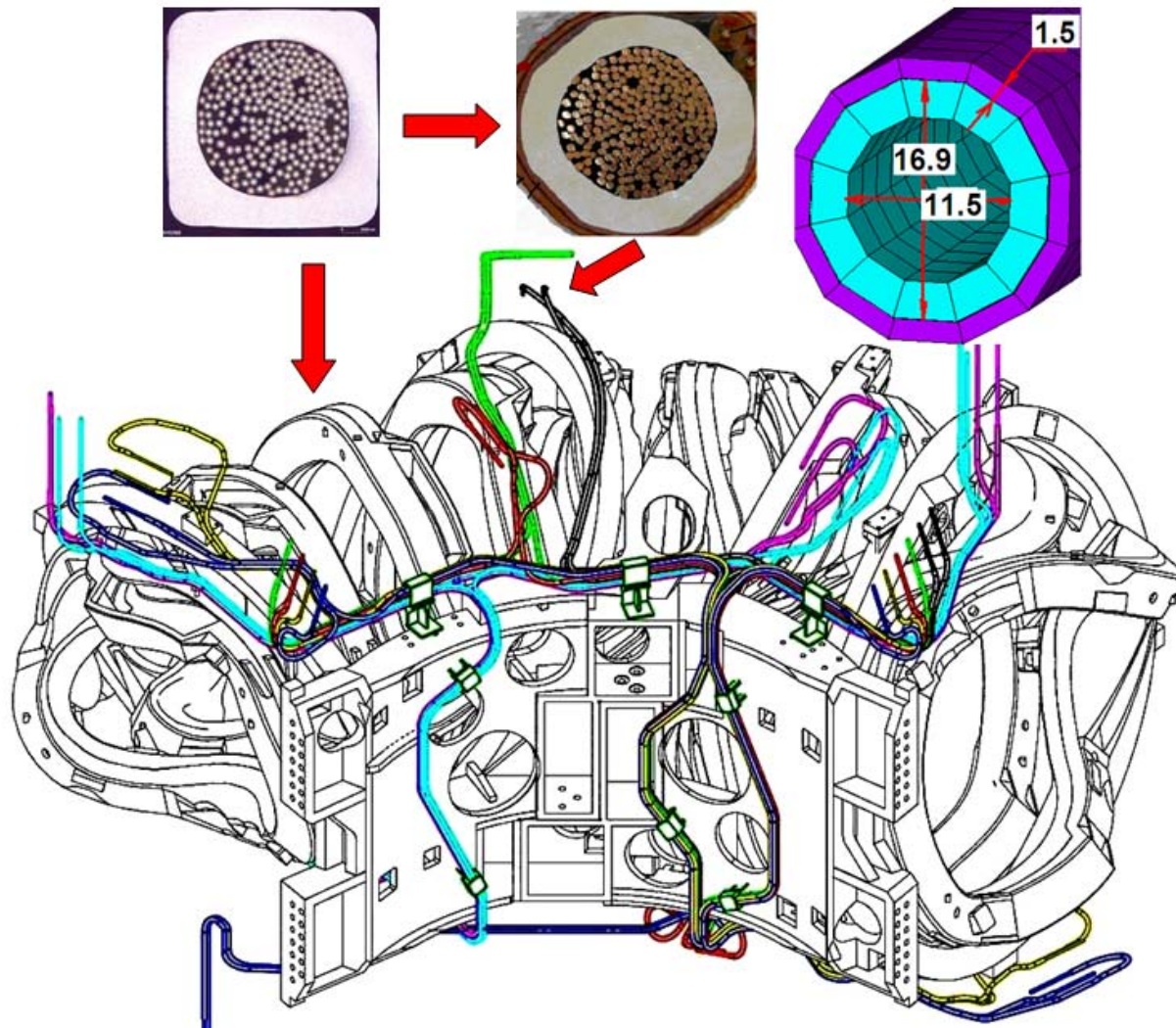
Design **validation** according to applicable codes and standards comprises **numerous simulations**.

Getting **structural response** of a single finite element model to **combined loading** from different sources, including electromagnetic transients is challenging.

Multifield finite element analysis is determined by the **iterative** nature of the **design process**.

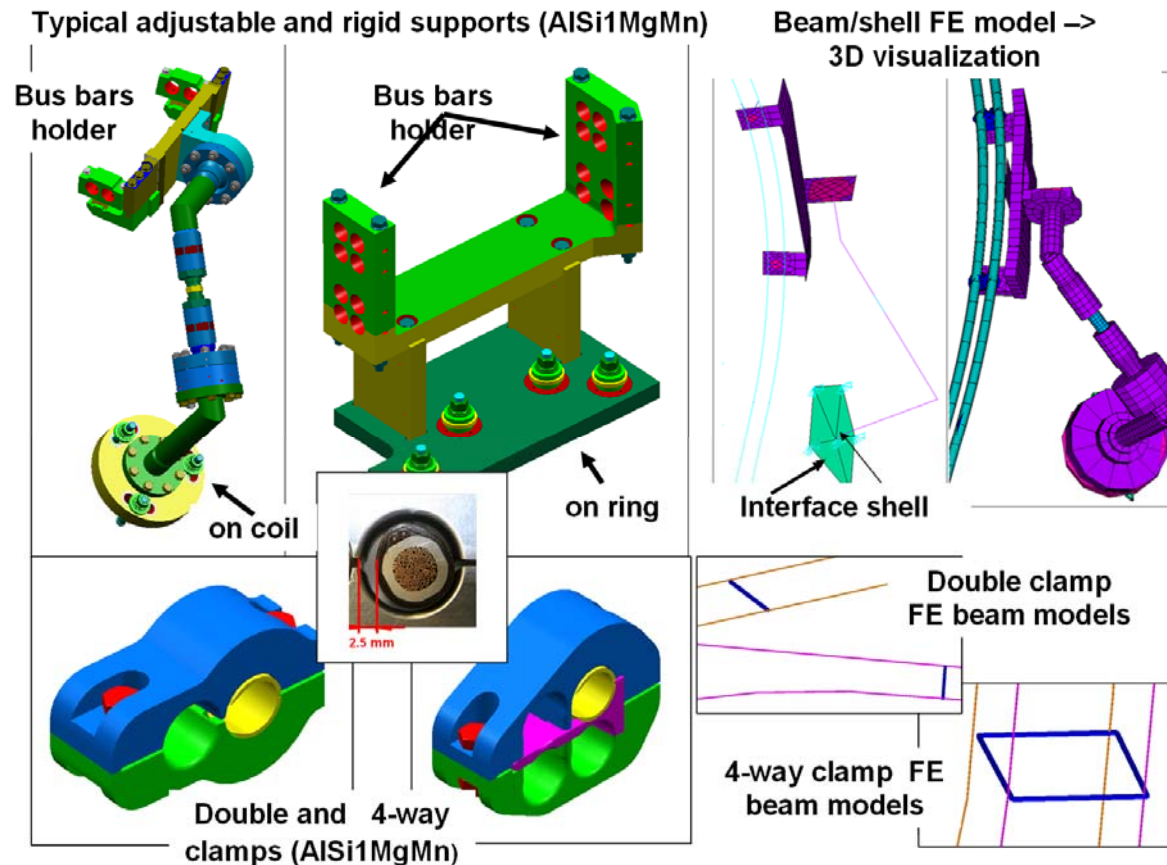
**Customized analysis strategies** required.

# Simplified Beam/shell Approach Busbar System for W7-X – Problem Description



- Bus to connect all identical coils
- Lorentz force
- Relative movement of coils and supports under magnet load
- Difference in temperature (contraction) of neighboring busbars at cool down
- Adjustability for tolerances
- Lack of space for supports
- Long and flexible busbars (121) with numerous supports (~400) and clamps (~400)
- Direct modeling for analysis from CAD seems impossible

# Simplified Beam/shell Approach Busbar System for W7-X – Beam/Shell Elements

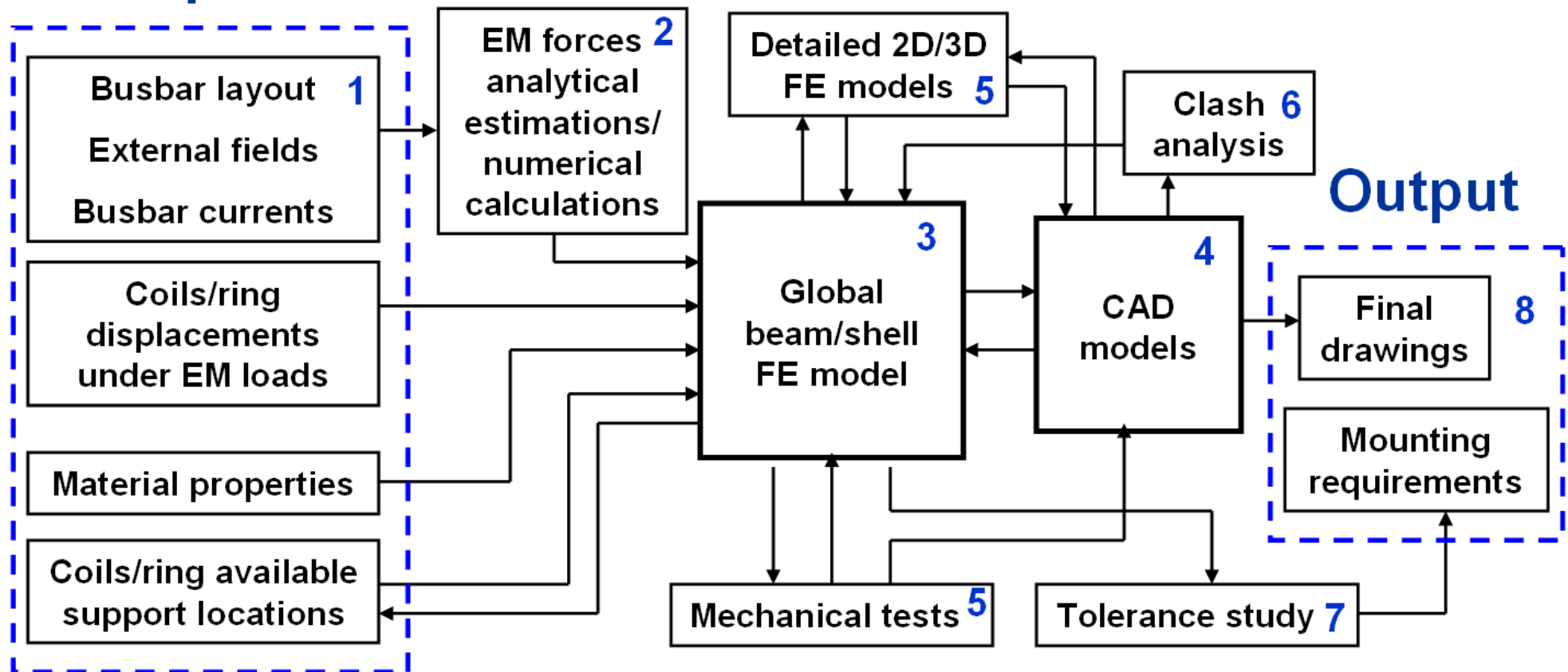


- Allows busbar assembly in tight space
- Keeps stresses in busbars below allowable values
- Limits busbar movements to avoid collisions

- 3D beam elements representing lines in space with arbitrary cross section for stiffness and stresses
- 3D shell elements representing surfaces in space with varying thickness
- Both directly supply main stress components required by design criteria
- 3D effects, like stress concentration, not regarded

# Simplified Beam/shell Approach Busbar System for W7-X – Design and Analysis Workflow

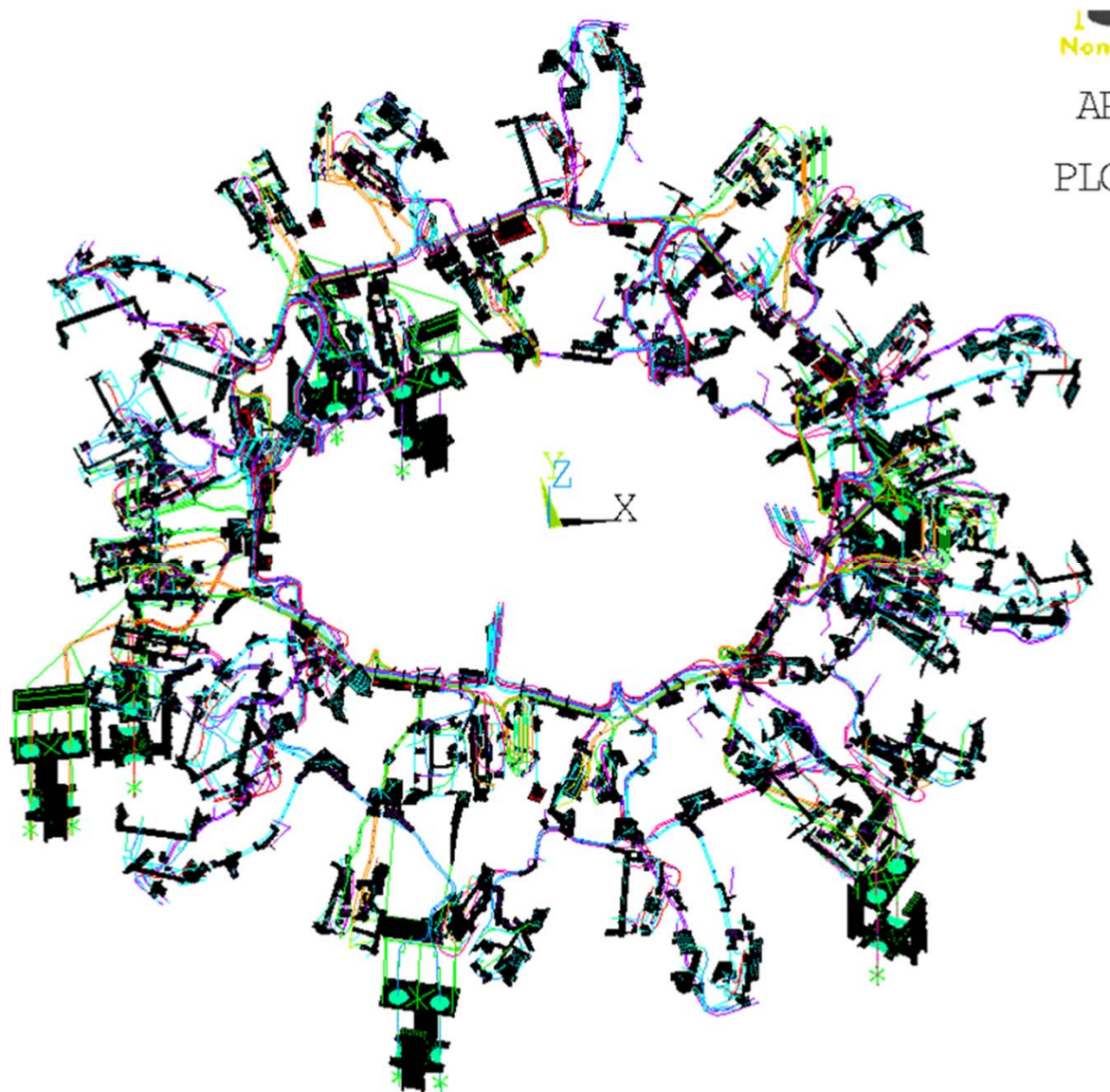
## Input



Multiple iterations of *design - global / local analysis – test*



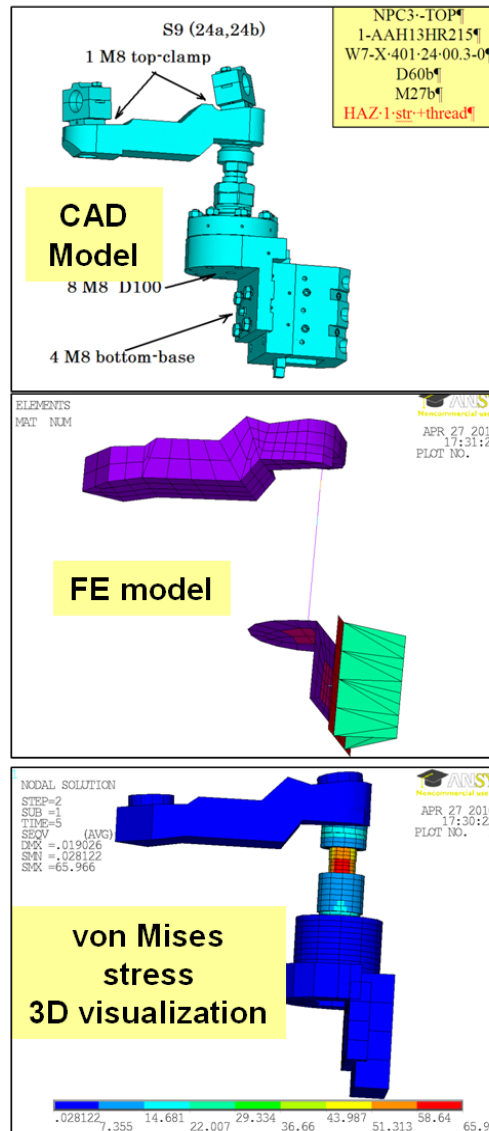
# Simplified Beam/shell Approach Busbar System for W7-X – Global FE Model



- Includes all busbars and supports
- Reflects main system features like stiffness and interaction
- Simple and flexible to changes
- Main stress components from 3D visualization of beam/shell elements
- Forces and moments for system analysis and changes, mechanical tests, and detailed 3D FE studies
- Runtime 30 min on office PC

# Simplified Beam/shell Approach

## Busbar System for W7-X – Detailed Analysis



### Loads and stresses in critical bolts

Support Bolts		Module 1		19.11.2009		runst_12																	
						M3		A3		L5		S7		MAX									
Coil	Support	Panin points	New points	Comment		N	M	S	F	Mb	S	F	Mb	S	F	Mb							
						bolts																	
NPC 1 Top	S1	2 4 8 16		top-clamp	1 M 8	44	116	1	14	168	8	49	116	1	14	245	11	14					
					1 M 8	110	43	2	16	168	8	49	116	1	14	245	11	14					
					1 M 8	110	43	2	16	168	8	49	116	1	14	245	11	14					
					2 M 6	105	5	139	162	24	24	24	24	24	24	24	24	24					
S3	6,12.5,11	15,20,14,19	bottom	1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
S4	7,13.7b,13b		top	1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
NPC 2 Top	S5	19,14	25,21	middle	1 M 8	26	105	12	1	11	111	3	20	85	8	19	84	3	1	28			
					1 M 8	26	105	12	1	11	111	3	20	85	8	19	84	3	1	28			
					1 M 8	26	105	12	1	11	111	3	20	85	8	19	84	3	1	28			
					1 M 8	26	105	12	1	11	111	3	20	85	8	19	84	3	1	28			
S6	20,15	26,22	base	1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
S7	22,21.7b,16	28,24.27	base	1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
				1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164					
NPC 2.3 Top	S8	29,19,22a,17a		top	1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164				
					1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164				
					1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164				
					1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164				
NPC 3 Top	S9a-new	24a,2b	29a,29b	bottom-base BB D60	1 M 8	21	87	105	7	12	121	29	16	84	10	61	47	61	7	139	82		
					1 M 8	24	104	87	114	3	11	121	24	16	83	105	8	62	29	13	04	117	114
					1 M 8	24	104	87	114	3	11	121	24	16	83	105	8	62	29	13	04	117	114
					1 M 8	21	87	105	7	12	121	29	16	84	10	61	47	61	7	139	82		
				top-clamp	1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164				
					1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164				
					1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164				
					1 M 8	31	118	44	1	11	164	104	1	11	164	104	1	11	164				

## Loads and stresses in aluminum thread

SUPPORT TREAS THREOMENTS & stresses																				
Moments - N'm, Stress - MPa						RUNST_12				17.11.09				MODULE 1						
***** Supports top HALF ****						HI		LS		BT		MAX						HAI		
		Moment	Nb	Sbend	Stor	Moment	Nb	Sbend	Stor	Moment	Nb	Sbend	Stor	Mtors	Mbsend	Stor	Sbend	Svm	Comments	
		Bzeta	Uls	Lls	Lls	Bzeta	Uls	Lls	Lls	Bzeta	Uls	Lls	Lls	MPa						
S1 bot_p2	M24	28	42	17	51	59	13	9	16	22	28	17	52	60	21	23	28	36	28	43
S1 bot_p2a	M20.	2	16	2	33	34	0	2	5	2	17	35	35	36	1	6	1	12	12	2
S2 bot_p4,10,3.9	M32.	72	207	14	78	82	35	1447	7	54	56	83	210	16	39	63	65	83	210	17
S3 bot_p6,12.5,11	M27.	2	46	1	37	37	38	123	15	99	103	5	4	2	35	35	22	81	6	37
S4 bot_p7,13,7b,13b	M27.	76	126	31	100	115	92	37	21	30	47	44	126	18	55	62	64	106	95	67
S5 bot_p19,14	M20.	5	4	5	9	13	6	5	10	14	5	2	6	5	1	5	1	6	5	5
S6 bot_p20,15	M27.	26	6	11	5	19	21	19	18	6	21	28	8	11	6	20	24	13	10	11
S7 bot_p22,17,21,16	M27.	1	58	0	48	46	20	79	8	63	65	1	20	56	56	1	4	51	52	20
S8 bot_p22,20,17a	M27.	7	8	3	69	69	37	58	16	5	73	73	1	5	73	73	1	50	56	68
S9 bot_p24a,24b	M27.	67	27	57	42	66	1	23	6	18	18	55	22	36	53	28	21	11	22	30

### Moments taken by spherical hinge

C5		C6		C7		C8		C9		C10		C11		C12		C13		C14		C15		C16		C17		C18		C19		C20		C21		C22		C23		C24		C25		C26		C27		C28		C29		C30		C31		C32		C33		C34		C35		C36		C37		C38		C39		C40		C41		C42		C43		C44		C45		C46		C47		C48		C49		C50		C51		C52		C53		C54		C55		C56		C57		C58		C59		C60		C61		C62		C63		C64		C65		C66		C67		C68		C69		C70		C71		C72		C73		C74		C75		C76		C77		C78		C79		C80		C81		C82		C83		C84		C85		C86		C87		C88		C89		C90		C91		C92		C93		C94		C95		C96		C97		C98		C99		C100		C101		C102		C103		C104		C105		C106		C107		C108		C109		C110		C111		C112		C113		C114		C115		C116		C117		C118		C119		C120		C121		C122		C123		C124		C125		C126		C127		C128		C129		C130		C131		C132		C133		C134		C135		C136		C137		C138		C139		C140		C141		C142		C143		C144		C145		C146		C147		C148		C149		C150		C151		C152		C153		C154		C155		C156		C157		C158		C159		C160		C161		C162		C163		C164		C165		C166		C167		C168		C169		C170		C171		C172		C173		C174		C175		C176		C177		C178		C179		C180		C181		C182		C183		C184		C185		C186		C187		C188		C189		C190		C191		C192		C193		C194		C195		C196		C197		C198		C199		C200		C201		C202		C203		C204		C205		C206		C207		C208		C209		C210		C211		C212		C213		C214		C215		C216		C217		C218		C219		C220		C221		C222		C223		C224		C225		C226		C227		C228		C229		C230		C231		C232		C233		C234		C235		C236		C237		C238		C239		C240		C241		C242		C243		C244		C245		C246		C247		C248		C249		C250		C251		C252		C253		C254		C255		C256		C257		C258		C259		C260		C261		C262		C263		C264		C265		C266		C267		C268		C269		C270		C271		C272		C273		C274		C275		C276		C277		C278		C279		C280		C281		C282		C283		C284		C285		C286		C287		C288		C289		C290		C291		C292		C293		C294		C295		C296		C297		C298		C299		C300		C301		C302		C303		C304		C305		C306		C307		C308		C309		C310		C311		C312		C313		C314		C315		C316		C317		C318		C319		C320		C321		C322		C323		C324		C325		C326		C327		C328		C329		C330		C331		C332		C333		C334		C335		C336		C337		C338		C339		C340		C341		C342		C343		C344		C345		C346		C347		C348		C349		C350		C351		C352		C353		C354		C355		C356		C357		C358		C359		C360		C361		C362		C363		C364		C365		C366		C367		C368		C369		C370		C371		C372		C373		C374		C375		C376		C377		C378		C379		C380		C381		C382		C383		C384		C385		C386		C387		C388		C389		C390		C391		C392		C393		C394		C395		C396		C397		C398		C399		C400		C401		C402		C403		C404		C405		C406		C407		C408		C409		C410		C411		C412		C413		C414		C415		C416		C417		C418		C419		C420		C421		C422		C423		C424		C425		C426		C427		C428		C429		C430		C431		C432		C433		C434		C435		C436		C437		C438		C439		C440		C441		C442		C443		C444		C445		C446		C447		C448		C449		C450		C451		C452		C453		C454		C455		C456		C457		C458		C459		C460		C461		C462		C463		C464		C465		C466		C467		C468		C469		C470		C471		C472		C473		C474		C475		C476		C477		C478		C479		C480		C481		C482		C483		C484		C485		C486		C487		C488		C489		C490		C491		C492		C493		C494		C495		C496		C497		C498		C499		C500		C501		C502		C503		C504		C505		C506		C507		C508		C509		C510		C511		C512		C513		C514		C515		C516		C517		C518		C519		C520		C521		C522		C523		C524		C525		C526		C527		C528		C529		C530		C531		C532		C533		C534		C535		C536		C537		C538		C539		C540		C541		C542		C543		C544		C545		C546		C547		C548		C549		C550		C551		C552		C553		C554		C555		C556		C557		C558		C559		C560		C561		C562		C563		C564		C565		C566		C567		C568		C569		C570		C571		C572		C573		C574		C575		C576		C577		C578		C579		C580		C581		C582		C583		C584		C585		C586		C587		C588		C589		C590		C591		C592		C593		C594		C595		C596		C597		C598		C599		C600		C601		C602		C603		C604		C605		C606		C607		C608		C609		C610		C611		C612		C613		C614		C615		C616		C617		C618		C619		C620		C621		C622		C623		C624		C625		C626		C627		C628		C629		C630		C631		C632		C633		C634		C635		C636		C637		C638		C639		C640		C641		C642		C643		C644		C645		C646		C647		C648		C649		C650		C651		C652		C653		C654		C655		C656		C657		C658		C659		C660		C661		C662		C663		C664		C665		C666		C667		C668		C669		C670		C671		C672		C673		C674		C675		C676		C677		C678		C679		C680		C681		C682		C683		C684		C685		C686		C687		C688		C689		C690		C691		C692		C693		C694		C695		C696		C697		C698		C699		C700		C701		C702		C703		C704		C705		C706		C707		C708		C709		C710		C711		C712		C713		C714		C715		C716		C717		C718		C719		C720		C721		C722		C723		C724		C725		C726		C727		C728		C729		C730		C731		C732		C733		C734		C735		C736		C737		C738		C739		C740		C741		C742		C743		C744		C745		C746		C747		C748		C749		C750		C751		C752		C753		C754		C755		C756		C757		C758		C759		C760		C761		C762		C763		C764		C765		C766		C767		C768		C769		C770		C771		C772		C773		C774		C775		C776		C777		C778		C779		C780		C781		C782		C783		C784		C785		C786		C787		C788		C789		C790		C791		C792		C793		C794		C795		C796		C797		C798		C799		C800		C801		C802		C803		C804		C805		C806		C807		C808		C809		C810		C811		C812		C813		C814		C815		C816		C817		C818		C819		C820		C821		C822		C823		C824		C825		C826		C827		C828		C829		C830		C831		C832		C833		C834		C835		C836		C837		C838		C839		C840		C841		C842		C843		C844		C845		C846		C847		C848		C849		C850		C851		C852		C853		C854		C855		C856		C857		C858		C859		C860		C861		C862		C863		C864		C865		C866		C867		C868		C869		C870		C871		C872		C873		C874		C875		C876		C877		C878		C879		C880		C881		C882		C883		C884		C885		C886		C887		C888		C889		C890		C891		C892		C893		C894		C895		C896		C897		C898		C899		C900		C901		C902		C903		C904		C905		C906		C907		C908		C909		C910		C911		C912		C913		C914		C915		C916		C917		C918		C919		C920		C921		C922		C923		C924		C925		C926		C927		C928		C929		C930		C931		C932		C933		C934		C935		C936		C937		C938		C939		C940		C941		C942		C943		C944		C945		C946		C947		C948		C949		C950		C951		C952		C953		C954		C955		C956		C957		C958		C959		C960		C961		C962		C963		C964		C965		C966		C967		C968		C969		C970		C971		C972		C973		C974		C975		C976		C977		C978		C979		C980		C981		C982		C983		C984		C985		C986		C987		C988		C989		C990		C991		C992		C993		C994		C995		C996		C997		C998		C999		C1000	
C5		C6		C7		C8		C9		C10		C11		C12		C13		C14		C15		C16		C17		C18		C19		C20		C21		C22		C23		C24		C25		C26		C27		C28		C29		C30		C31		C32		C33		C34		C35		C36		C37		C38		C39		C40		C41		C42		C43		C44		C45		C46		C47		C48		C49		C50		C51		C52																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									

## Loads and stresses in aluminum weld

SUPPORT ALU welds - MOMENTS & stresses

Moments - N'm, stress - MPa

RUNST\_12 17.11.09 MODULE 1

\*\*\*\*\* Np's top HALF \*\*\*\*

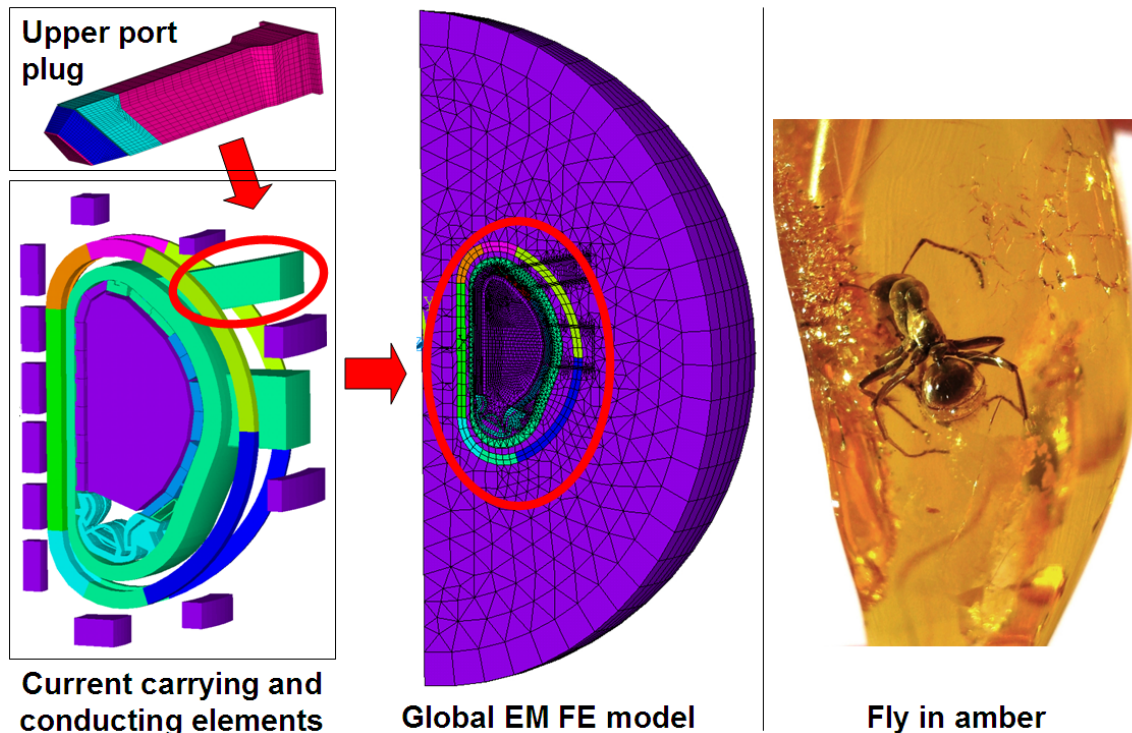
	HI				LI				LS				ST				MAX				Mben for test							
	Mtor		Sben		Mtor		Sben		Mtor		Sben		Mtor		Sben		Mtor		Sben									
	MAT	N° m	MPa	N° m	MPa	N° m	MPa	N° m	MPa	N° m	MPa	N° m	MPa	N° m	MPa	N° m	MPa	N° m	MPa	N° m	MPa							
S3_top	117	2	61	0	15	25	38	111	5	28	25	5	61	1	15	15	22	32	4	10	11	38	111	5	28	29	116	28
S3_bot	117	65	95	0	15	18	42	142	8	25	65	8	23	27	32	34	5	11	9	14	25	36	111	9	14	25	36	111
S3	120	2	140	0	53	38	145	7	55	5	120	1	49	49	22	134	4	51	33	38	145	7	55	5	120	1	49	49
S7_top	10	0	68	0	17	17	46	61	5	16	18	12	76	2	19	19	25	63	1	15	16	46	76	6	19	19	76	6
S7_mid	117	1	60	0	15	15	20	75	2	19	18	1	71	0	18	18	10	63	1	16	16	20	75	2	19	19	76	6
S7_bot	118	33	7	8	15	45	65	8	16	19	5	68	24	8	17	51	45	61	11	16	65	65	8	16	19	76	6	
S9(p27)_bot	114	268	9	67	10	24	1	6	68	254	9	63	65	26	20	3	260	10	25	26	74	268	9	67	69	277	10	
S9(p27)_top	114	216	9	29	33	10	50	1	12	13	63	59	22	26	20	3	5	8	74	115	9	29	33	10	50	1	12	13
S9(p27)_mid	117	292	15	57	9	160	12	47	47	47	47	47	47	47	47	47	117	292	15	50	56	292	15	50	56	292	15	
S9(p27a_24b)	117	67	40	8	29	13	1	23	9	9	55	31	7	18	14	28	20	4	8	8	87	40	8	10	18	72	10	

- Extensive output from global model for post-processing
- Forces, moments, main stresses in supports' critical locations
- Forces, moments on bolted interfaces re-calculated in semi-automated way into the bolts direct stresses
- Torque on the bus/clamp bond post-processed



# Multifield Analysis Including Electromagnetic

## ITER Diagnostic Port Plug – Problem Description

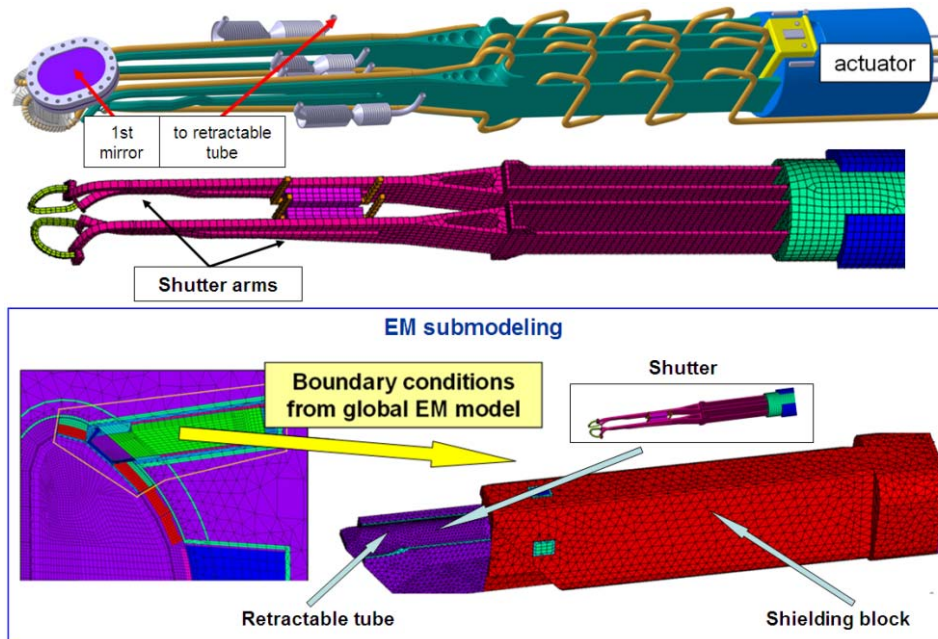


- Simulation of components in an ITER diagnostic port plug to combine loading from different sources including electromagnetic transients
- Electromagnetic model combines electrically conducting parts and contacts as well as air elements
- Filling air gaps of structural parts and applying far field boundary condition is challenging

Approaches starting from global simplified electromagnetic model:

- Force transfer to detailed structural model
- Analytic electromagnetic sub modelling
- Numerical electromagnetic sub modelling omitting air elements in order to allow for detailed component model

# Multifield Analysis Including Electromagnetic ITER Diagnostic Port Plug – Sub-modeling

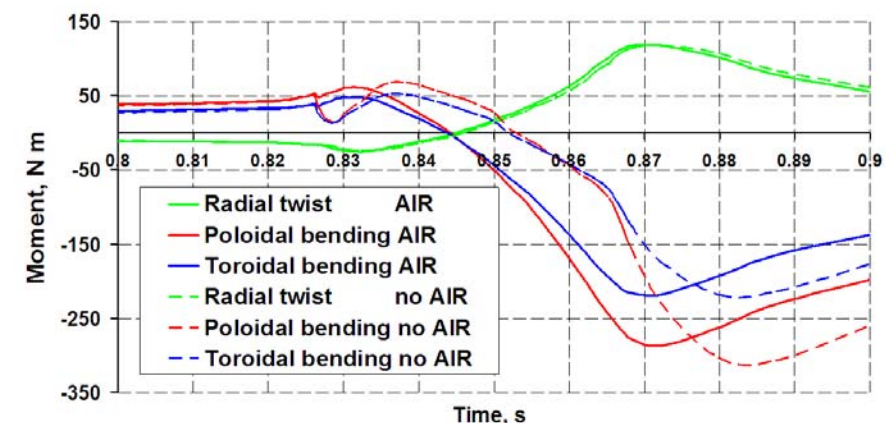


Separate EM analysis, simplified model

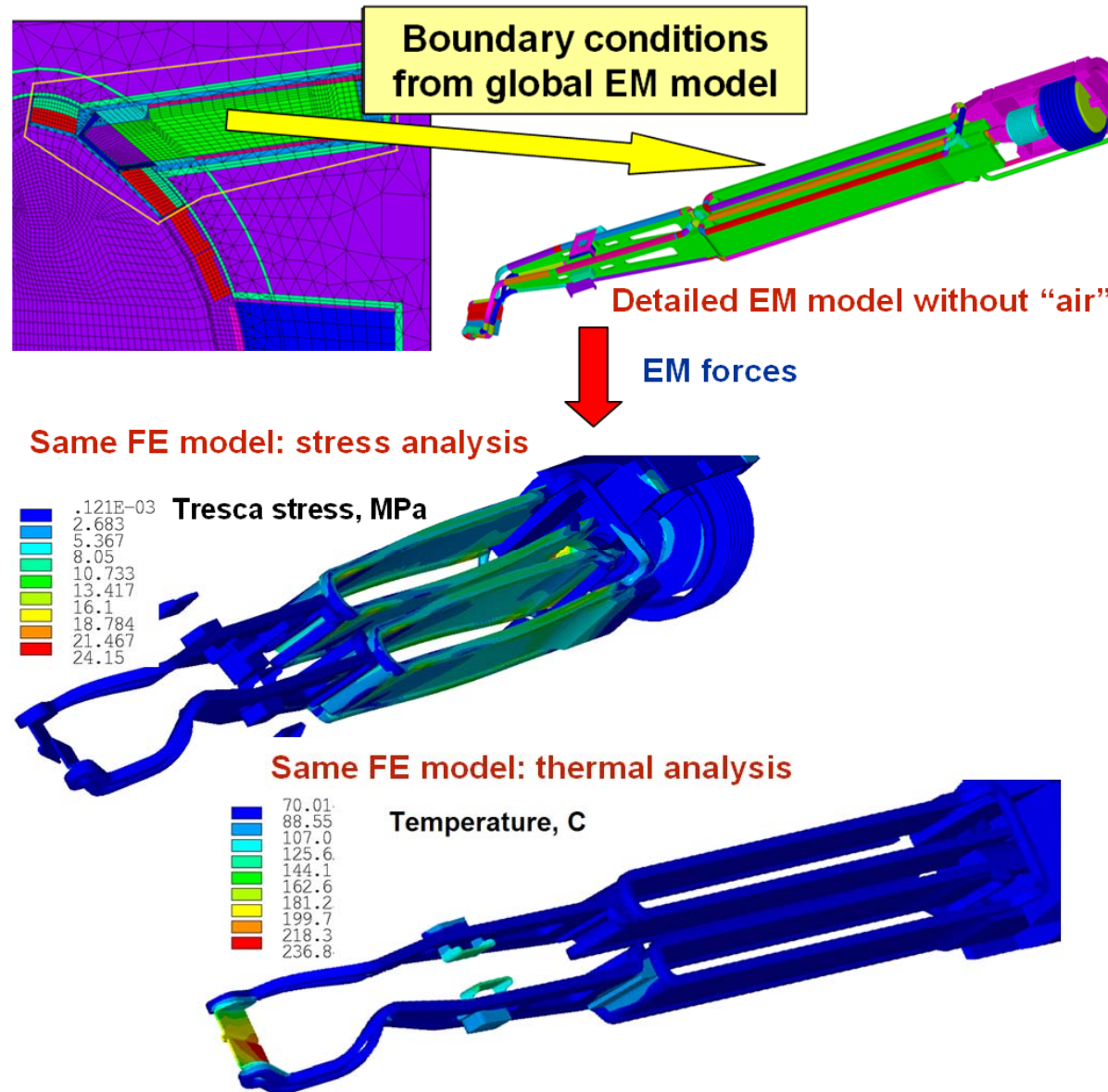
- Local model of shield block and inner components with air elements between multiple conducting parts
- Shutter geometry drastically simplified, electrical connections carefully modeled
- Boundary conditions for outer nodes derived from global model

EM analysis w/o air elements

- Analysis repeated without air elements
- Effect of eddy currents on total field negligible (skin depth criterion)
- Sufficient accuracy even without air elements



# Multifield Analysis Including Electromagnetic ITER Diagnostic Port Plug – Multifield Model

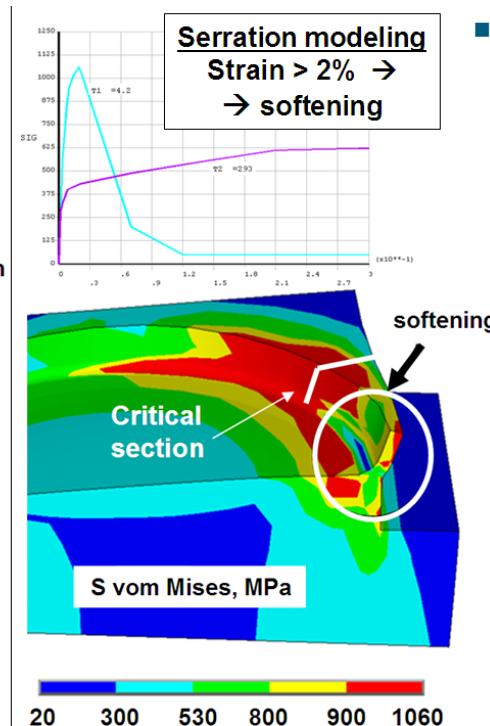
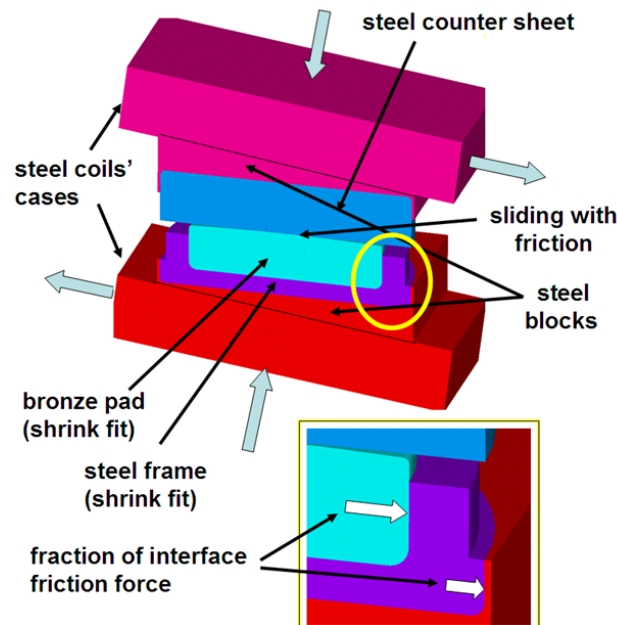
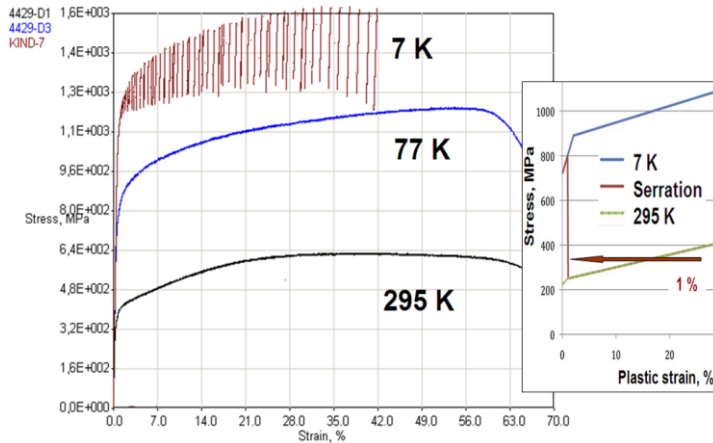


- Simplified model suited for concept iteration but not for detailed analysis
- Validation of electromagnetic analysis without air elements allows for multifield analysis of shutter arms using detailed model fitting all analysis types



# Engineering Material Model for Serration Effect

## W7-X Magnet System – Problem Description



- Cryogenic steel to operate in elastic range accounting for serration effect at cryogenic temperatures
- Narrow supports of W7-X magnet system work outside elastic range
- Development of approach
  - Elasto-plastic analysis with no load carried above 2% strain found out critical cross-section
  - Limit analysis with serration effect assuming step change of material behavior from 7K to room temperature above 1% strain found limiting load



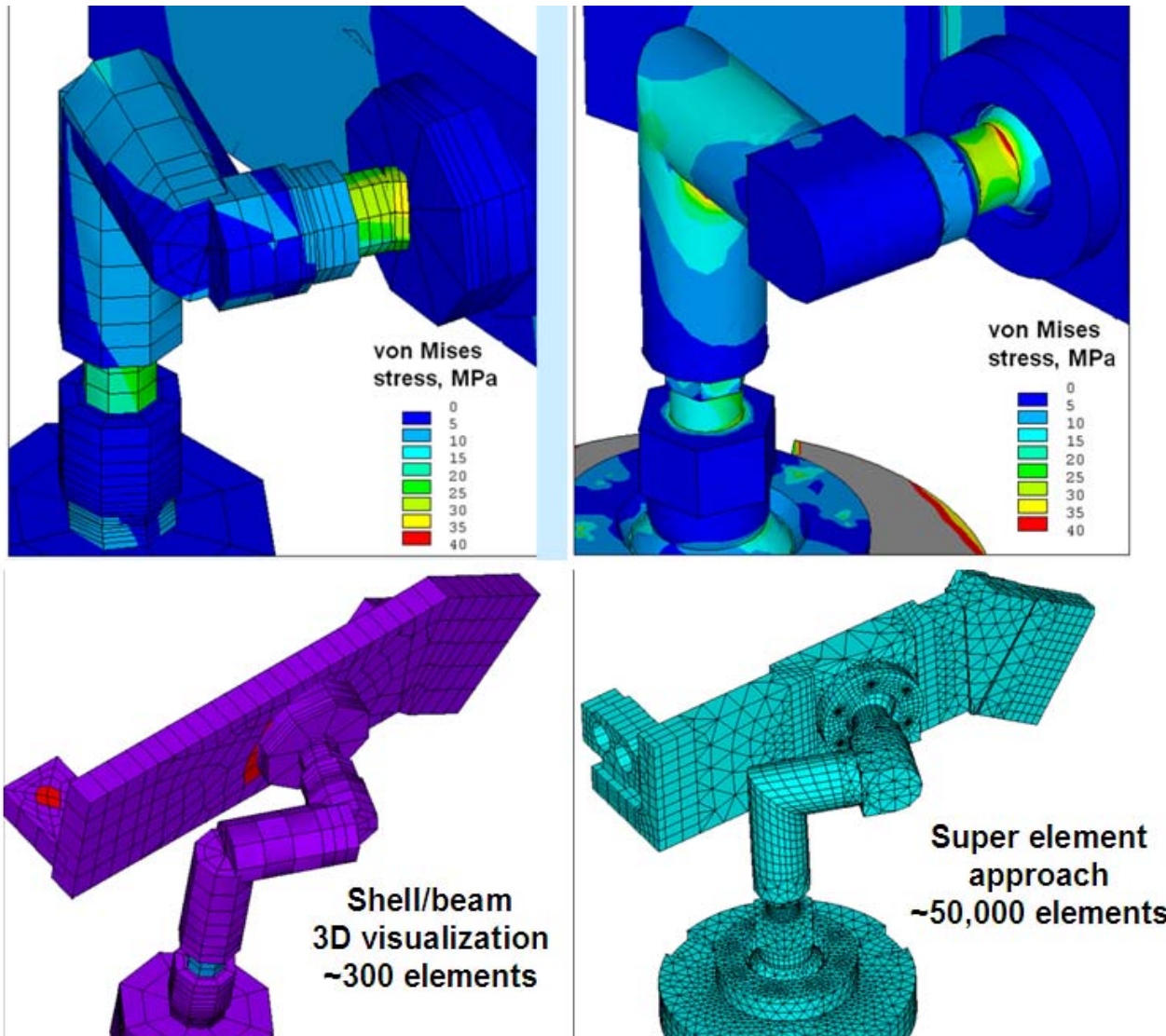
# Conclusions

## Numerical models

- To be built up with clear understanding of the analysis goals and expected results,
- To be reasonably simplified, flexible for changes,
- To use 2D, axisymmetric, or beam-shell modeling whenever appropriate,
- Should be parametric for maximum modification flexibility,
- Should find tradeoff between simulation time and precision in case of time consuming dynamic analyses.

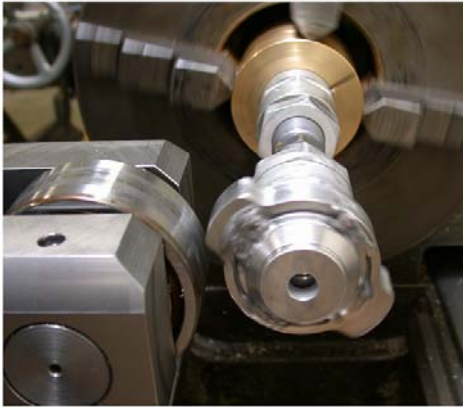
Only the finally selected design option to be checked in detail, desirably both by analysis and test.

# Simplified Beam/shell Approach Busbar System for W7-X – Local FE Models



- Simplified models of critical supports validated against 3D detailed ones
- Stiffness and main stresses of both models agree well
- Simplified models directly supply forces and moments for further submodeling of critical connections or for mechanical tests

# Simplified Beam/shell Approach Busbar System for W7-X – Testing



Cyclic bending test of aluminum threaded connection at RT



Cyclic bending test of aluminum weld at RT

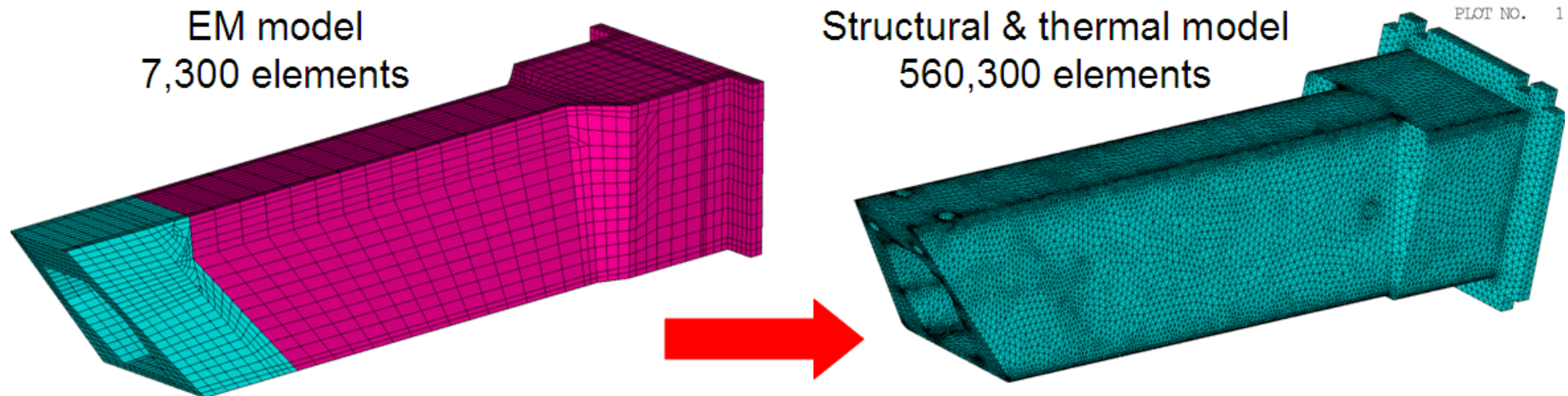


- Busbar bending – non-insulated versus insulated
  - Wearing of busbar insulation in the clamps/supports – sliding with compression
  - Busbar insulation – compression, tension, shearing
  - Clamp – torque taken by glued connection
  - Bolts – required torque to create bolt preload, loss of preload, cyclic loading etc.
  - Spherical hinges of the supports under applied moment – RT and 77 K
- Cyclic bending of aluminum threaded connection and aluminum weld



# Multifield Analysis Including Electromagnetic

## ITER Diagnostic Port Plug – Load Transfer



Models having different mesh and even slightly different geometry

- External code seeking for each “loaded” node of the source model the geometrically nearest nodes of the target model implying
  - A sound choice of an epsilon neighborhood for target nodes
  - Reliable checks of calculated global and local moments on the structure